Passive Artificial Ventilation of Hypoxic Estuarine Benthic Environments: A Feasibility Study

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ABSTRACT


The feasibility of utilizing buoyant moored underwater wings to ventilate benthic environments in estuaries was explored by way of a pilot field and modeling study. The concept involves reduction of stratification and downward advection of water by lift-generated vortex wakes. Results show that stable wings, that produce high lift at low Reynolds numbers, can be constructed and deployed relatively simply and that such wings generate significant vortex circulation and descending wakes. Strong stratification increases the rate of wake decay; however, by deploying the wings beneath the level of maximum Brunt-Vaisala frequency the effectiveness of the wings is greatly increased.

INDEX WORDS: Low dissolved oxygen, wings, wake vortices, destratification.

INTRODUCTION

It is well documented that many benthic regions of the Chesapeake Bay and its tributaries experience conditions of low dissolved oxygen for part of each year (OFFICER et al., 1984; SELIGER et al., 1985; Kuo and NEILSON, 1987). Hypoxic conditions can occur not only in deeper sectors of the Chesapeake Bay, but also in the deep portions of tributaries to the Chesapeake Bay, notably the Rappahannock and York Rivers (Figure 1), when water temperatures exceed 20 °C (Kuo and NEILSON, 1987). Hypoxia is a consequence of many factors, including oxygen consumption by water column organisms and the decay of benthic organic matter exceeding the combined horizontal and vertical import of new oxygen (OFFICER et al., 1984).

Stable density stratification of the water column is the major impediment to the vertical transport of oxygen from upper to lower layers; reduced stratification increases the vertical diffusivity of oxygen (WEBB and D’ELIA, 1980; OFFICER et al., 1984; Kuo and NEILSON, 1987). It has been established that vertical stratification is least or negligible during spring tides whereas stratification and attendant hypoxia are most pronounced during neap tides (HAAS, 1977; HAYWARD et al., 1982). Processes, natural or anthropogenic, that reduce stratification and increase vertical mixing are likely to increase the downward transport of oxygen and thereby improve the quality of the benthic environment.

However, it has been difficult to design feasible, cost-effective, long-term, artificial remedies for hypoxia or anoxia. It is obvious that the development of affordable methods for reducing stratification and ventilating deeper layers is desirable. The approach that comes readily to mind is the direct pumping of air or oxygenated water to the bottom layers. Unfortunately, such a method involves relatively expensive machinery, requires substantial energy consumption, and is labor intensive.

For any artificial method of water column ventilation to be seriously countenanced for prolonged use, the method must be passive in the sense that the energy required is derived from the naturally-occurring currents rather than from external sources. A passive technique that has been demonstrated to be effective in controlling sedimentation in harbors involves the deployment of moored wings, which interact with tidal currents...
THEORETICAL BACKGROUND

Density Stratification

The strength of vertical density stratification in the water column is expressed by the Brunt-Vaisala frequency, $N$, which is approximately

$$N = \left( \frac{g}{\rho} \frac{\partial \rho}{\partial z} \right)^{1/2}$$

where $g$ is the acceleration of gravity, $\rho$ is water density, and $z$ is the vertical coordinate (positive upward) (PHILLIPS, 1977). The Brunt-Vaisala frequency (which has units of radians per second) is equivalent to the highest internal gravity wave frequency that the stratified water column can sustain. The corresponding Brunt-Vaisala period, $T_n$, in seconds is

$$T_n = \frac{2\pi}{N}.$$

Density stratification in estuaries is caused by vertical gradients in salinity and temperature with salinity gradients making the stronger contribution.

The square of the vertical velocity gradient (or shear rate), $\partial U/\partial z$, provides a measure of the turbulent stresses that may act against stable stratification to mix the water column. The overall stability of the water column can be expressed by the dimensionless gradient Richardson number, $R_i$, given by

$$R_i = \frac{N^2}{(\partial U/\partial z)^2}.$$  

(e.g. PHILLIPS, 1977). The water column is typically stable when $R_i > 0.25$; the higher the value of $R_i$, the greater is the degree to which stratification is likely to suppress vertical mixing (e.g. DYER, 1986).
Wing-Induced Vortices

A wing creates lift by imparting downward momentum (downwash) to the fluid moving relative to the wing. This causes the pressure on the upper wing surface to be lower than ambient and that on the lower surface to be higher than ambient. The resulting steep pressure gradient between the lower and upper surfaces near the wing tips gives rise to a swirling circulation called wing-tip vortices. These vortices are the primary source of the mixing the wings are intended to induce. Pairs of such vortices are responsible for the familiar contrails often visible in aircraft wakes (e.g. Scorer and Davenport, 1970). Figure 3 is a definition sketch illustrating the relationships between the critical wing dimensions, notably the span, B, and chord, C, wake width, L, the descent distance, h', of the wake below wing level, the separation, b, between vortex pairs, and vertical descent velocity, w.

The chord-based Reynolds number $R_e$, is a critical parameter in determining whether or not a wing will generate sufficient lift and, hence whether sufficiently strong wing-tip vortices will be created. The chord based Reynolds number is defined as

$$R_e = \frac{UC}{\nu}$$

where $\nu = \text{kinematic viscosity of water (approximately } 10^{-6} \text{ m}^2 \text{ sec}^{-1})$. The normalized measure of wing lift is the lift coefficient, $C_L$, defined as
where $S$ is the area of the wing. The lift coefficient $C_L$ depends on $R_e$ as well as the wing aspect ratio, 

$$A_e = \frac{B^2}{2S} = \frac{B}{C}.$$ 

Sarpkaya (1983) conducted a series of controlled laboratory experiments on wings in water and found that vortices were well developed when $R_e$ was in the range of $4 \times 10^4$ to $5 \times 10^5$; fully developed vortices may be expected when $R_e \geq 10^6$. Increasing stratification decreases the lifespan of the vortices in the wake of a wing (Sarpkaya, 1983; Greene, 1986). Greene (1986) found the lifetime of vortices to be about $T_n/4$.

After being generated, vortices begin to decay due to ambient environmental effects such as density stratification (Saffman, 1972; Sarpkaya, 1983) and fluid turbulence (Crow, 1970; Tombach, 1973; Bilanin et al., 1978). An aim of the current study was to design wings that would produce vortices capable of surviving long enough in the anticipated stratified environment to produce the desired oxygen transport and mixing while decaying rapidly enough in a non-stratified turbulent environment to prevent undesirable bottom scouring. Therefore, it was necessary to estimate vortex motion and decay characteristics in terms of readily available parameters characterizing both the lifting wing and the background environment.

The method used in this study was that of Greene (1986) which includes an analytical model of linear density stratification and a semi-empirical model of turbulence and viscous effects. It does not include any effects due to cross currents or vortex decay due to interaction with the bottom.

The Greene (1986) model results in a relatively simple equation for the motion and decay of vortices in a stratified and turbulent environment. In this model the distance, $h'$, of descent (below the wing in the negative $z$ direction) is normalized by the vortex spacing, $b$, and is $\frac{h'}{b}$. Time, $t$, is expressed in dimensionless form as $T = \frac{tw_o}{b}$ where $w_o$ is the initial descent velocity of the vortices.

The initial descent velocity, $w_o$, is a key variable in determining the effectiveness of the technique; $w_o$ increases with increasing flow velocity, $U$ and lift coefficient $C_L$ in accordance with

$$w_o = K_c \frac{C_L U}{A_e}$$

where $K_c$ is a constant that depends on wing design ($K_c = 0.14$ in our case). Typical lift coefficients are in the range of 0.8–1.2 when the Reynolds number is high so $w_o$ is principally a fraction of $U$. The initial vortex circulation, $\Gamma_0$, is

$$\Gamma_0 = \frac{C_L U B^2}{2bA_e}.$$  

The vortex circulation $\Gamma$ after decay is then

$$\Gamma = \Gamma_0 \frac{d\xi}{dT}.$$  

In the case of long-lived vortex wakes generated by wings in an unstratified or weakly stratified atmosphere, the second term ($\alpha \ldots$) in equation 6 is important. However, for our problem, stratification and turbulence are both very important and, under these environmental conditions, the total wake excursion is short and this permits this term to be dropped allowing equation 6 to be simplified to a general analytical form

$$\frac{d\xi}{dT} + \alpha \left(\frac{d\xi}{dT}\right)^2 + \beta \frac{d\xi}{dT} + \gamma \xi = 0.$$
and
\[ \frac{d\zeta}{dT} = \left( \frac{D_1}{D_1 - D_2} \right) e^{\gamma T} - \left( \frac{D_2}{D_1 - D_2} \right) e^{\alpha T} \] (14)

where
\[ D_1, D_2 = -\frac{\beta}{2} \pm \sqrt{\left(\frac{\beta}{2}\right)^2 - \gamma^2} \] (15)

In designing wings in the current study, two sets of conditions were considered. First are the conditions conducive to hypoxia and for which the wings are designed to enhance mixing of the water column. In these conditions of strong stratification and large gradient Richardson number, ambient turbulence is suppressed and vortex motion and decay are determined to a large degree by stratification effects alone. For design purposes in these conditions, \( \beta \) can also be set equal to zero to estimate vortex characteristics and equation 13 becomes
\[ \zeta = \frac{1}{\gamma} \sin \gamma T. \] (16)

The normalized vortex strength, \( d\zeta/dT \), from equation 14 is
\[ \frac{d\zeta}{dT} = \cos \gamma T, \] (17)

and the maximum nondimensional depth to which the vortices travel is \( 1/\gamma \).

The second set of conditions of interest pertains to small values of the gradient Richardson number when there is sufficient turbulence to mix the water column and there is no stratification. In this case one would like to determine the possibility of vortices reaching the bottom with sufficient strength to produce scouring. For this case, \( \alpha \) and \( \gamma^2 \) are set equal to zero and equation 13 becomes
\[ \zeta = (1 - e^{-\gamma T})\beta^{-1}, \] (18)

the vortex strength ratio, equation 14, becomes
\[ \frac{d\zeta}{dT} = e^{-\gamma T} \] (19)

and the maximum nondimensional descent distance of the vortices is \( 1/\beta \). Note that vortex strength decays exponentially in turbulence as contrasted with cosine decay in stratification. In addition, turbulence causes a vortex-pair instability that can further accelerate decay (Crow, 1970). Therefore, if there is significant turbulence, there is a greatly reduced chance of strong vortices reaching the bottom to produce scouring.

**Implications for Wing Design**

In order to design a wing for a given environment, the values of the parameters which make up the coefficients, \( \alpha, \beta, \) and \( \gamma^2 \) must be anticipated. The coefficient \( \alpha \) is an empirical constant which can be taken to be 0.23 for wings operating at relatively low Reynolds numbers (Greene, 1986). Its value is not important for the results of this study since the second term in equation 6 can be ignored.

Using the definitions of \( \alpha, \beta, \) and \( \gamma \) given in equations 7-9, the maximum dimensional vortex descent distance with stratification only, \( \zeta_{\text{max}} \), becomes (with \( b/B = 0.8 \))
\[ \frac{b}{\gamma} = \frac{T_n w_0}{4.25} \frac{C_L U T_n}{34A_e}, \] (20)

and with the turbulence only becomes
\[ \frac{b}{\beta} = \frac{0.98Bw_0}{q} = \frac{0.12BC_L U}{qA_e}. \] (21)

For example, consider an environment that has a Brunt-Vaisala period, \( T_n \), of 600 sec when stratified, a turbulence level, \( q/U \), of 3% when unstratified, and a current at wing level of 1 m/sec. Assuming a wing lift coefficient of 1.0 and aspect ratio of 4.0, the maximum vortex descent in the stratified water would be about 4.4 m, independent of the span of the wing. For the unstratified turbulent conditions, the maximum descent depends on wing span and for these conditions is about one wing span. However, vortex strength decays exponentially and is reduced by \( 1/\beta \) by the time the vortices have descended \( 1/\beta \) wing spans.

If additional vortex migration is needed in stratified conditions, either the lift coefficient can be increased or the wing aspect ratio reduced. However, wings in water currents typically operate at relatively low Reynolds numbers and may have a significantly lower maximum lift coefficient than an aircraft wing unless designed specifically for the low Reynolds number conditions. In reducing the aspect ratio of the wing there are also other considerations. This can be done, for example, by increasing wing chord while holding the span constant (increasing wing area) or by reducing span while holding area constant. In the
first case, increasing wing area will increase lift and thus alter the anchoring requirements. In the second case, the reduced span means that more wings will be required to provide the same area of coverage. Therefore design of a wing or an array of wings involves the tradeoff of several parameters and the optimum will depend on the design environment, construction and anchoring methods, and costs.

**STUDY METHODS**

**Wing Design and Construction**

Our research program involved an iterative, interactive mix of wing design, theoretical and computer modeling, and field experiments. Limited laboratory experimentation in a recirculating flume was involved in initial stability tests of wing scale models prior to prototype fabrications; however, key experiments were conducted under field rather than laboratory conditions since the conditions that we studied cannot be properly scaled down to flume dimensions. The most important function of the laboratory experiments was to obtain guidance on stable tethering configurations for the wings. Three stages were involved in wing development and testing. Initially, a small prototype was constructed of plywood and deployed for short periods in strong tidal currents in the lower York River (Figure 1) in March and April, 1989. Divers observed wing behavior and stability; tethering arrangements were modified several times until a stable configuration was achieved.

In the second stage, a full-sized swept wing with a span of 6.10 m and a chord of 1.22 m was constructed of plywood and fiberglass and deployed in a density-stratified reach of the York River for a period of six weeks (April–May 1990) during which time flow and density structures in the wake of the wing were observed at different tidal phases. Following the testing and some modifications of the full-sized wing, three additional such wings were constructed and all four wings were deployed in the lower York River over a relatively soft bed in an array with the aim of determining whether or not wing arrays were likely to cause undesirable bottom scour.

**Numerical Modeling**

Vortex descent and decay rates in the wake of a wing were modeled numerically for varying conditions of stratification using a finite difference approach. The finite difference form of equation 6 can be written

\[
\frac{\bar{z}_{i+1} - \bar{z}_{i-1}}{2} = \alpha (\bar{z}_{i} - \bar{z}_{i-1})^2 - \beta (\bar{z}_{i} - \bar{z}_{i-1})^2 \Delta T - \gamma \bar{z}_{i} \Delta T_{v} \tag{22}
\]

where \(\alpha, \beta, \) and \(\gamma\) are evaluated in equations 7–9. Equation 22 can be readily solved given initial conditions, wing dimensions, wing deployment depth, \(C_{t}, C_{n}, U,\) and \(N.\)

**Field Measurements**

Several techniques were employed to measure flow structures and stratification upstream and in the wakes of the wings. At each anchor station we measured the salinity, temperature and depth profile (and, hence, the density profile) together with current velocity by means of an ENDECO Model 174 current meter/CTD system. This system utilizes a ducted impeller current meter with a 2-axis flux-gate compass, a thermistor with an accuracy of \(\pm 0.2 ^\circ C,\) an inductive conductivity probe with an accuracy of \(\pm 0.55\) millisiemens/cm, and a potentiometric pressure transducer. The system has a 128 k solid state memory. We used an Applied Microsystems STD-12 as a CTD backup. To the ENDECO current meter, we also attached a Marsh-McBirney electromagnetic current meter (1.2 cm sphere) oriented to measure the flow components orthogonal to the dominant current, \(U (i.e.\) the vertical, \(w,\) and y-axis, \(v,\) components associated with vortices) during periods of absolutely calm surface conditions. We also used a R&D Instruments Model DR 1200 acoustic-doppler current profiler system to obtain continuous profiles of the different flow constituents (including the vertical component). This instrument operates at 1200 kHz.

Repeated side scan sonar surveys were used to evaluate the impact of the 4-wing array on the bed. These surveys were conducted immediately prior to and at one-week intervals during the one-month deployment of the array. The surveys utilized an EG&G Model SMS 960 Sea Floor Mapping System (105 kHz). This system produces images that are fully corrected for slant range and vessel speed. An overlap of 50% ensured complete mosaic coverage of the affected bed area.

Observations of wing orientation, behavior, and stability and limited adjustments to wing moorings were made directly by divers. Unfortunately, the near-zero visibility of the York River experiment sites precluded the use of flow visualization techniques or underwater photography. Field deployments and observations utilized the 20-m R/V
Bay Eagle and the 14-m R/V Langley. Navigation was by LORAN-C.

**WING CONFIGURATION, STABILITY, AND MOORING**

Criteria and Constraints

Considerable effort was devoted to experimenting with different wing shapes and mooring arrangements in an effort to optimize lift, stability, and anchoring practicality. Specifically, we sought to maximize the lift coefficient, $C_L$, and thereby the strength and duration of vortices while limiting the combined positive buoyancy and total lift to values low enough to allow the wings to be held in place by anchors weighing 750 to 1,000 kg. In all cases pairs of railroad wheels chained together or dual wheel and axle assemblies were used as anchors for each wing; heavier anchors could not be practically deployed from our 20 m research vessel. Although high chord-based Reynolds numbers (equation 4) are normally needed to ensure maximum vortex intensity, the maximum wing size is limited by the weight of the anchor. Other constraints include the requirement that wings not dive or swerve and that they immediately realign themselves to face into currents of changeable direction.

**The Prototype Wing**

Initial modeling indicated that lift coefficients near 1.0 could probably be generated in very strong flows ($U \approx 1$ m sec$^{-1}$) by a straight wing with a NACA-type foil shape and a sharp trailing edge. A prototype wing of such design was constructed for use in the initial experiments (Figure 4). The wing had a chord width of 1 m and a span of 2 m; a tail fin assembly provided high stability. It was constructed of plywood sealed with a plastic coating and contained flotation to maintain positive buoyancy. Swivel joints mounted on sail track on the underside of the wing made it possible for divers to adjust the aspect of the wing.

Figure 4. Small prototype wing used in initial experiments.

**A Low-Reynolds Number/High-Lift “Water Wing”**

We addressed the initial dilemma of accommodating the requirement for a high lift coefficient while keeping wing size to a minimum by adopting a foil shape specially designed to produce relatively high lift at low Reynolds numbers (Pfenninger et al., 1988). Specifically, we chose the ASM-LRN-010 airfoil cross section (Figure 5) which is noticeably distinguished by its downturned trailing edge. This airfoil shape, which gives the wing a relatively high nose-down pitching moment, can provide acceptable lift with $R_e$ values in the range $1.5-5.0 \times 10^5$. This means that for flows as weak as 0.15 m sec$^{-1}$, airfoil $C_L$ values in the neighborhood of 1.0 can be achieved with a chord, $C$, (Figure 3), of only 1.2 m. The actual $C_L$ is also dependent on the angle of attack, $\theta$, and plan-view wing shape. For the idealized case of a straight wing with $\theta = 6^\circ$, a $C_L$ value of 1.3 is predicted for $R_e = 2.5 \times 10^5$. The swept wing design that we used reduces $C_L$ somewhat so that a maximum value of about 1.0 is predicted for a current speed, $U$, of 0.25 m sec$^{-1}$.

A swept-back plan configuration was used instead of a straight design in order to improve directional and pitch stability. Figure 6 shows the

Figure 5. The ASM-LRN-010 foil cross section configuration of the large, low Reynolds number, high-lift wing.

Figure 6. Plan shape and dimensions of the large, low Reynolds number, high-lift wings.
wing plan shape. The four full-sized wings that we constructed have spans, B, of 6.0 m, chords, C, of 1.2 m and sweepback angles of 20°. The wing area, s, is 7.3 m². The wings were constructed of wood, foam and fiberglass; they have a net positive buoyancy of about 350 kg and weigh about 100 kg in air. Initial field tests showed that the swept-wing design was stable, but required a tail assembly to maximize stability and to enable tethering points to be placed far enough behind the wings’ center of buoyancy. Figures 7a and 7b show a full-sized wing.

The center of the pressure loading or distribution around the NASA-LRN-010 airfoil is approximately located at 0.4 C (measured from the airfoil leading edge). Longitudinal stability requires that the pitching moment about the center of gravity should become increasingly negative (nose down) as lift increases. This allows the airfoil to return to its equilibrium or trimmed pitch attitude if disturbed by a vertical eddy or some other transitory flow phenomenon. A wing can thus be designed to be longitudinally stable by sweeping it back.

In hydrodynamic tethered applications the stability effects of the buoyancy force must also be considered. The estimated center of buoyancy of the water wing is at 0.37 C. The main load bearing tether points were on the wing span (the primary structural member) which is located near the point of maximum thickness at 0.35 C. Initially a three point tether was used for the wing. The nose tether was located at approximately 0.10 C on the wing center span position while the two span tether points were located approximately at the 0.40 B position. These locations were chosen on the basis of minimizing wing bending loads. This resulted in a tether centroid that was close to the centers of lift and buoyancy of the wing. Fabrication considerations prohibited employing a hard point near the wing trailing edge for an aft tether, due to insufficient material thickness. Twin aft booms were therefore employed to provide an aft tether point that could keep the tether centroid aft of the lift and buoyancy centers. Horizontal and vertical tail surfaces were mounted on the tail booms to provide an additional margin of longitudinal and lateral stability in the event that a large eddy or ship wake came close to the wing.

The wing requires an inherent directional stability to align itself with the prevailing tidal current. If the swept water wing encounters a current that is off center, the leading wing will experience a drag force that is greater than that on the trailing wing. This produces a stabilizing vertical moment that aligns the water wing into the current. The tether system and the sweep back prevents rolling instability. The inherent directional stability may also be designed into a straight wing by the use of a dihedral angle. However sweep back is a more attractive solution from a structural point of view.

Results from the Small Prototype Wing

Stratification was very weak at the time the prototype wing was deployed. However, the results demonstrated that even a small wing can be quite effective in generating descending wakes containing relative strong vortices even though the resulting wakes are narrow and, thus, likely to affect a small bed area. An example from a set of field measurements of horizontal and vertical flows made in the wake of the wing is shown in Figure 8. Horizontal current velocities were about 0.22 m sec⁻¹; R, was about 3 × 10⁵. As the figure indicates, the wing produced strong vertical fluctuations and a descending mean flow in the region immediately downstream of the wing. Modeling results suggest that for a mean horizontal current speed, U, of 0.50 m sec⁻¹, 3% turbulence, and no stratification, the wake should have descended roughly 1.5 m over a horizontal distance of 100 m.

Field Results with a Single Large Wing

Relatively strong stratification was present throughout most of the period of deployment of a full-sized wing in the York River estuary in April and May, 1990. The wing was deployed at a depth of 3.5 m below mean water. Water depth at the site was 12 m. Profiles of density, ρ, and Brunt-Vaisala frequency, N, as they existed at the site during ebbing tide on 26 April 1990 are shown in Figure 9. The vertical components of mean flow upstream and at two positions downstream of the wing, as measured with the acoustic doppler current profiler are plotted against depth in Figure 10; the corresponding horizontal current speed is also shown. Figure 10 shows that, upstream of the wing, net vertical flows were negligible; however, in the wake region a short distance downstream of the wing, significant descending flows with speeds of over 2 cm sec⁻¹ were observed. These
Figure 7. Photos of the full-sized wing (a) being lowered from the research vessel; (b) floating at the surface.
descent velocities were on the order of those predicted by equation 6. Notably, the descending flows extended to depths well below the depth of the maximum pycnocline (~ 4.2 m; Figure 10).

More pronounced density stratification prevailed at the time of field observations on 8 May 1990. Variations with depth of \( \rho, N, U, \) and \( R \), upstream of the wing and at stations 10 m and 30 m downstream of the wing are portrayed in Figures 11 to 13. Although subtle differences are apparent from a comparison of the upstream and downstream profiles, we can see no obvious differences in \( N \) which best indexes the strength of the stratification. The \( T_n \) value corresponding to the peak \( N \) at about 2 to 2.5 m in Figures 11a to 13a was about 50 sec. The most pronounced contrasts between upstream and downstream were in the values of the gradient Richardson number, \( R_g \), which underwent a marked decrease in the wake region of the wing. Similarly, the variances of the \( w \) and \( v \) flow components (which index vortex intensity) orthogonal to the primary flow, \( U \) were appreciably larger downstream of the wing than was the case at the upstream station (Figure 14).

The tendencies for \( R_g \) to be reduced and for vortex intensity to be greater in the wake of the wing both suggest that the wing was effective in causing mixing and reducing the strength of stable stratification.

Numerical Modeling Results for the Single Wing Case

The numerical model was run for the case of the stratification and current profiles observed on 8 May 1990. In different runs the wing was assumed to be situated above (Figure 15) and below (Figure 16) the steepest region of the pycnocline. For the first case, with wing depth below the surface taken as 2.5 m, the wing would have been...
located near the position of maximum N (Figure 11a) and shortest \( T_n \). Owing to the strong current at this depth (Figure 11b), relatively high values of 0.391 m\(^2\) sec\(^{-1}\) and 1.34 cm sec\(^{-1}\) are predicted respectively for initial vortex intensity \( \Gamma_0 \), and wake descent velocity, \( w_0 \). However, as shown in Figure 15, the strong density stratification at and immediately below the wing level should have caused rapid vortex decay and a slowing of the wake descent rate, \( w \). Within 70 m downstream of the wing, relative vortex intensity, \( \Gamma / \Gamma_0 \), would have decreased to 0.20; over the same distance the wake would have descended only 1.3 m. For this case, we could not expect wing-induced vertical mixing to reach below mid-depth. The implications of this exercise are that when the maximum pycnocline steepness occurs at a relatively small fraction of the total depth, as is often the case in deeper regions of an estuary, wings placed in the upper layers of the water column are likely to be ineffective in improving the quality of the benthic environment.

For the hypothetical case of a wing deployed at a depth of 5.0 m, and thus below the region of strongest flows, smaller values of 0.273 m\(^2\) sec\(^{-1}\) and 0.94 cm sec\(^{-1}\) are predicted for \( \Gamma_0 \) and \( w_0 \). Despite this reduction in vortex intensity, however, the significantly lower density gradients at these depths would be responsible for appreciable reduction in vortex decay rate. Consequently, the wake should penetrate to over 2.0 m and reach 150 m downstream before \( \Gamma / \Gamma_0 \) reduced to 0.20 (Figure 16). The rate of vortex decay could have been further reduced without a substantial reduction in \( \Gamma_0 \) by placing the wing a meter or so deeper (i.e. at \( \sim 6.0 \) m); the abrupt decrease in vortex decay rate at about 1 m below the wing (at \( x = 50 \) m; Figure 16) occurs after the wake has descended into a lower region of relatively uniform density (Figure 11a).

RESULTS FROM AN ARRAY OF FOUR WINGS

An array of four wings was deployed off Gloucester Point in the lower York River in water depths of 10 to 15 m for a five-week period embracing the month of October 1990. Two pairs of wings were separated by a downflow distance of 300 m; individual members of each pair were aligned side by side with their centerlines 50 m apart. Hence, the array defined a rectangle 56 m \( \times \) 300 m. The wings were located about 5 to 5.5 m below the surface. The array was deployed over a very soft bed surmounted by large hydroid clusters attached to patchy shell beds. This bottom type was referred to by Wright et al. (1987) as "lower estuary muddy shoals."

Originally, the multiple wing experiment was intended to address two questions: (1) can prolonged deployment of multiple wings above an
otherwise hypoxic environment significantly increase benthic dissolved oxygen? and (2) Is such a deployment likely to cause detrimental bed scour? Unfortunately we were unable to address the first question because, at the time of the experiment, a prolonged period of low runoff had resulted in negligible stratification; no hypoxic condition existed. However, the lack of stratification improved our confidence in the answer to the second question since the bed was not insulated from vortices. Figure 17 depicts the vertical profiles of \( \rho \), \( N \), \( U \), and \( R_i \) that were typical of the entire period of deployment of the multi-wing array. A nearly homogeneous vertical density structure (Figure 17a), and a nearly uniform current speed throughout the upper 6 m of the water column (Figure 17b) are apparent. Profiles measured at different distances downstream of wings differed negligibly from those shown in Figure 17. Numerical model runs for the 4 October 1990 set of conditions (Figure 17) and for the actual wing deployment depth of 5.3 m suggest that comparatively strong wing-induced vortices should have experienced very
gradual decay (Figure 18). The wakes should have penetrated to nearly 4.5 m below wing level and reached nearly 300 m downstream before the relative vortex intensity, $T/T_0$, diminished to 0.20 (Figure 18). This suggests that even though the wakes should reach the benthic layer of the water column, vortices reaching the bottom should be too weak to cause appreciable scour. The modeling results also indicate where scour might be expected if it occurred: in this case scour induced by the upstream pair of wings during ebbing tide should appear within 100 m downstream of the downstream wing pair. The reverse would have applied for flood-tide generated vortices.

Wing shadows, clearly visible on side-scan sonographs, provided well defined reference points for comparing successive side-scan sonar surveys. The major features apparent from a survey at the time of deployment were depressions adjacent to raised hummocks. The depressions are formed by scour in the lee of large hydroid clusters attached to shell bioherms (WRIGHT et al., 1987). Other features included grass beds, at the eastern end of the transect. Side-scan sonar imagery obtained
Figure 13. Variations with depth of (a) $p$ and $N$ and (b) $U$ and $R$, measured 30 m downstream of a large wing in the lower York River on 8 May 1990.

at the end of the deployment period displayed no discernable differences from that obtained prior to and at the beginning of the wing deployment. We infer from this that the wings produced no consequential changes in bottom topography despite the fact that the soft bottom is relatively easy to erode.

**DISCUSSION AND CONCLUSIONS**

Our studies so far indicate that it is quite feasible to construct and deploy rather robust wings that are highly stable underwater in relatively strong currents and that induce significant vortices within descending wakes. For construction of multiple wings using a mould, the cost is estimated to be on the order of $1,000 per wing (excluding anchors). Hence, it is conceivable that in cases where the value of a benthic resource is high enough to justify the expense and effort, extensive arrays of large wings could be deployed for prolonged periods. At this stage, however, we can offer no conclusions as to the effectiveness of such arrays in increasing dissolved oxygen in the benthic environment. Benefits additional to in-
Figure 14. Variations with depth of the variances of the two components (v and w) of flow orthogonal to the main axis of flow (U).

Figure 15. Numerical modeling results predicting the relative vortex strength, \( \frac{V}{V_0} \), and wake descent distance, \( y \) as functions of distance downstream of a large wing assumed to be moored at 2.5 m below the water surface within a water column having density and velocity structures identical to those shown in Figure 11.

creased dissolved oxygen may also be envisioned; for example increased vertical mixing and downward transport above a shellfish bed may enhance the flow of food. In other applications, LAWS et al. (1988) showed that wing foils used in an outdoor flume increased the production of microalgae. Long term monitoring studies are needed before the net benefits (or adverse impacts) of the method can be properly assessed.

The results in hand offer instructive insights into the most effective deployment techniques. In any ventilation strategy involving the use of wings,
it is essential to know, beforehand, the vertical density, dissolved oxygen, and current profiles that are most likely to prevail in association with hypoxia or anoxia. In common cases where the maximum density gradients and flow velocities are related to a relatively shallow surface layer of low density water, our modeling results indicate that wings placed within the upper layer may not succeed in ventilating deeper areas. A greater likelihood of success can probably be achieved by deploying at greater depths where \( N \) (and the rate of wake decay) are lower even though lower current speeds at those depths will reduce initial vortex intensity. The latter problem can, of course, be overcome by increasing wing size: \( \Gamma_0 \) can be doubled by increasing \( B \) and \( C \) by a factor of 1.4 (equation 11). Where deployment capabilities (e.g. vessel size) permit, increased wing size offers the additional advantage of increasing the width of a ventilated swath. For cases where the dissolved oxygen profile dictates that oxygen be imported from the upper layer, we can imagine a tiered arrangement of multiple wings with smaller wings in the upper layer and larger wings situated at greater depth and at an appropriate distance downstream.

The pilot study reported here is only a first step. The large scale practicality and cost effectiveness of the technique we describe cannot be evaluated until a wing array has been applied for a prolonged period and the results carefully and systematically monitored and compared to results from a nearby control site.

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LITERATURE CITED

ENVIRONMENTAL PROTECTION AGENCY (EPA), 1983. Chesapeake Bay Program: Findings and Recommenda-
Figure 17. Variations with depth of (a) ρ and N and (b) U and Ri, measured in the lower York River on 4 October 1990 at the time of deployment of a four-wing array.
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Figure 18. Numerical modeling results predicting the relative vortex strength, \( r/v \), and wake descent distance, \( y \) as functions of distance downstream of a large wing assumed to be moored at 5.3 m below the water surface (the average actual moored depth of the four wings) within a water column having density and velocity structures identical to those shown in Figure 17.


RESUMÉ

On a exploré sur une zone test et sur modèle la faisabilité d'un système sous marin de brassage pour aérer les environnements benthiques des estuaires. L'idée générale implique une réduction de la stratification et de l'advection verticale induite par l'effet de remontée tourbillonnaire de la remous. Les résultats montrent que l'on peut facilement construire des ailettes stables produisant une forte remontée pour de faibles nombres de Reynolds; elles peuvent être déployées relativement simplement, engendrer une circulation tourbillonnaire et un remous descendant. Une forte stratification augmente le taux de l'atténuation du remous; pourtant si les ailettes sont déployées en dessous du niveau de fréquence maximale de Brunt-Väisälä, l'efficacité des ailettes est largement accrue. — Catherine Bouquet-Bressolier, Geomorphologie EPHE, Montrouge, France.

RESUMEN

La posibilidad de utilizar alas sumergidas, ancladas al fondo y en boyancia propia para sistemas bentónicos ventilados en estuarios se exploró en campos piloto y modelos. Este concepto implica una reducción de la estratificación y de la advección de agua hacia abajo por generación de estelas de vórtices. Los resultados muestran que alas estables, que producen gran sustentación a bajos números de Reynolds pueden construirse con relativa sencillez que estas alas generan una circulación de vórtices significativa y
estelas descendentes. Una fuerte estratificación aumenta el rango de decrecimiento de la estela, sin embargo, desplazando las alas bajo el nivel de la máxima frecuencia de Brut-Vaisala la efectividad de las alas aumenta.—Department of Water Sciences, University of Cantabria, Santander, Spain.